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Three-dimensional(3D) printing in forensic science–An emerging technology in India

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ABSTRACT

Three-dimensional(3D) scanning and printing technologies has proved to be a boon and revolutionized Indian society in recent years. 3D printing is slowly gaining popularity in the fields of forensics due to its capability to provide information in all three axis (x, y and z) when compared to 2D photographs.The technology is actively being used in the fields of forensic medicine, anthropology, ballistics and odontology.3D printing allows better visualisation, interpretation, preservation and analysis of the evidence. The present article highlights the applications of 3D printing and presents current needs to develop and incorporate 3D printing technology in Indian forensics.

1. Introduction

Three-dimensional (3D) printing is a technique used to produce a realistic physical 3D structure from a computer-aided design (CAD) model or a digital 3D model [1]. The terminology behind ‘3D printing’ may be applied to several processes in which material is powdered, assembled or solidified under computer control to build-up a 3D object [2], with material usually attached together layer by layer. 3D printing technology was introduced by engineers dedicated to the development of structural models with simple and efficient performance after which over the past decade there has been rapid development in 3D printing techniques and materials [3]. Consequently, the technology was introduced to health sciences to improve the fields of medicine and dentistry especially when it comes to maxillofacial surgery, radiology/imaging and anatomy [4,5]. However, in spite of obtaining satisfactory outcomes in medical and dental fields, very few instances have been reported in forensics where 3D printing is being used. The present paper would discuss 3D printing technology and demonstrates the application of 3D printing technology from medicolegal and forensic viewpoint.

2. 3D printing technology-An overview

Digital imaging and communications in medicine (DICOM) images are used for generating 3D-printed models that provides both tactile feedback and tangible depth information of anatomic and pathologic states of an object [6]. 3D printers generally accept standard tessellation language (STL) file format that define surfaces as a collection of triangles (called facets) that fits together like a jigsaw puzzle. In general, 3D model can be printed from any volumetric imaging or surface scanned dataset, such as computed tomography scans, intraoral, or laboratory optical surface scan data [6]. A newer format called additive manufacturing file format (AMF), was approved by the American Society for Testing and Materials ASTM International in June 2011, to overcome many of the limitations of the simple STL format, such as enabling the user to incorporate features including surface texture, colour, and material properties into each part [7]. The process of 3D printing can be divided into three parts: image acquisition, image processing, and 3D printing. The quality of the 3D printed model depends on the technology such as fused deposition modelling (FDM), Stereolithography (SLA), digital light processing (DLP), Photopolymer jetting (PPJ), Powder binder printers (PBP), and Selective laser sintering (SLS) [8]. FDM is one of the early techniques in which 3D printers have robotic extruders that move through a stationary frame or have a stationary extruder and a movable framework [9,10]. Biodegradable polymeric acid (PLA) is a commonly used material; or similar materials such as polyvinyl chloride (PVC), nylon, acrylonitrile butadiene styrene (ABS) and investment casting wax have been used as key

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components of scaffolding structures. [10,11]. SLA provides a better resolution and utilizes a scanning laser to build sections -one layer at a time, in a vat of light-cured photopolymer resin where light sensitive polymer is cured layer by layer and hardened in UV oven. [9,12,13]. Whereas DLP uses a projector light source for layer-by-layer curing of the liquid resin with 35–100 microns resolution [14,15]. SLS uses a scanning laser that fuses fine material powder to create layer-by-layer structures with high-resolution level (60 μm) [16–19]. PPJ utilizes light-cured resin materials and print heads similar than those found in an inkjet printer (but considerably more expensive), to put down layers of photopolymer that are gently cured with each movement of the print head. [9] Complex geometry and very fine detail are possible– as little as 16 microns resolution [20]. PBP uses a modified inkjet head to print; basically, liquid droplets to infiltrate a layer of powder, layer by layer. The accuracy as well as strength obtained is less [20].

3. Illustrations of 3D printing in Forensics

A handful of authors have recognised the importance of 3D printing technology in forensic investigation. There are few cases reported where 3D printing has been used as demonstrative evidence in court. Baier et al. [21] in 2018 in their paper "Introducing 3D Printed Models as Demonstrative Evidence at Criminal Trials" demonstrated decision making process for presentation of 3D prints in court. The case report presented one of the first court trial in UK in which two offenders were accused for homicide. A section of skull was submitted for micro-Ct which was subsequently 3D printed and presented in court as demonstrative evidence for better understanding of pathological facts [21]. In another media article reported in 2015 a 3D printed murder weapon (bottle) was used by the prosecution, and the defendant was asked to demonstrate how the bottle was held during infliction [22]. It was quoted by the experts, that the technological approach was used for first time to explain the facts in court. In another murder trial in England, of a six-year-old the court had asked for 3D print of head CT-scan of victim to gain clarity on the cause of death [23]. In another case report from Poland [24] where 3D printing technology was used by investigators to explain the hypothesis for mechanism of injury.

Exhaustive researches are in progress to validate and demonstrate the application of 3D printing in forensic science. Carew et al. [25] conducted a study to assess the accuracy of different 3D printers for producing the replicas of bone. They compared the virtual models and their 3D prints, which showed minimal variation. It was concluded that for forensic anthropological evidence reconstruction, the modelling parameters influence the accuracy of 3D prints and SLS technology was considered to be most accurate. In another study the surface quality of the SLS printed human bone was assessed where it was concluded that 3D prints can be used as demonstrative evidence in court to exhibit gross features. [26] Errickson et al. [27] emphasized on the presentation of visual media to jury for better understanding, where they conducted a mock courtroom exercise to assess different mediums of visualisation viz photographs, virtual models and 3D prints. The results demonstrated that the juror understanding was better with the use of 3D modalities. In a short communication Ebert et al. [28] emphasized the importance of 3D prints and 3D imaging for proper visualisation and assessment. In the series of work, the authors highlighted the application of 3D scanning and printing in simulated forensic case scenarios [29–32].

4. Applications of 3D printing in Forensic Science

1 **Documentation** – Human remains offer conclusive proof in the area of forensics; nevertheless, the justice system mostly depends upon photographs and electronic copies in case owing

Fig. 1. 3D printed models of mandible and skull for documentation.

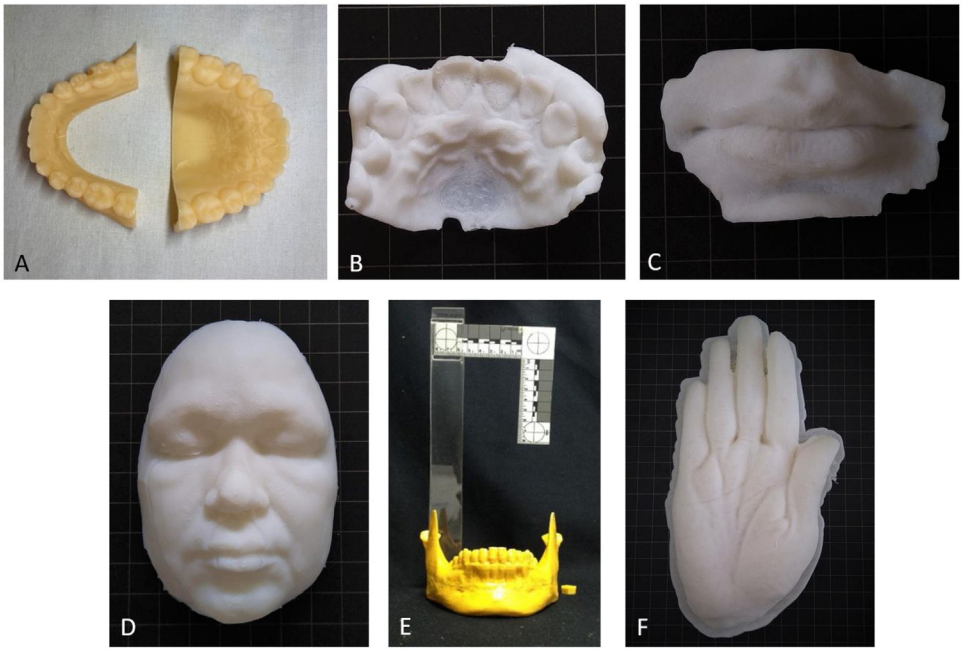

Fig. 2. (A) 3D printed upper and lower dentition for morphometric analysis, (B)3D printed rugae (C) 3D printed lips for cheiloscopy (D)3D printed face for future referral (E) 3D printed mandible (F) 3D printed Palm.

to a range of ethical and legal problems inherent with the storage, transport and representation of human remains to the trial and the jury. [33] In such situations, 3D printing can be used to produce realistic three-dimensional replicas of human remains from facts, that can serve to convey important details to the court and the jury, without offending anybody or causing bias [34]. Moreover, 3D models can also be transferred to other forensic experts, allowing them to consult on cases without having to transport the remains [35]. (Fig. 1)

Another positive aspect of 3D printed model relies on the possibility of perpetuating the evidence. Recently, virtual autopsy has emerged in the forensic field that enables a detailed, accurate visualization and analysis of the deceased. [36–38] Because in virtual autopsy most *postmortem* (PM) images are acquired as DICOM files or even surface scanned objects, 3D printing the files as realistic models becomes completely feasible. With the acquired PM images and the printed 3D models in hands, forensic experts are able to revisit the case without exhumation. Additionally, the eventual need of presenting the case in court becomes more palpable with the reproduced models (e.g., body parts).

With the popularization of 3D printing worldwide, devices and facilities became more accessible to those who seek for technological performances in the daily medical/dental routine. Experts must be aware of this phenomenon because soon 3D printed models will be part of the *antemortem* (AM) armamentarium for comparative human identification.

2 **Human Identification -** An accurate 3D model of a dentition may be useful in age estimation, for example in determining the status of the dentition. A 3D-printed model obtained from postmortem computed tomography (PMCT), for example, can help to minimize some of the difficulties found in traditional autopsies, such as examination of an individual due to rigor mortis or lack of proper visualization. [39] Similarly, a 3D model of the maxilla and mandible can also be used for age estimation, sex determination using various metric and non-metric traits. It has been demonstrated that dimensional changes between the tooth and the 3D models of the tooth is very discrete or even null [40]. In addition to that the accurate 3D printed model of skull would further aid in positive identification. The decomposition of human remains is inevitable and the soft tissues are the most affected. 3D scanning and printing of sinuses, face, finger prints, lip prints, palatal rugae or palm prints would not only aid in morphometric analysis but also would serve as evidence for future referral. (Fig. 2)

3 **Dental Anthropology and Comparative Dental Anatomy:** Dental anthropology is one of the few areas of forensic odontology where the application of 3D printing is constantly encouraged. An accurately printed dental model could help improve the accuracy of population identification from the non-metric dental traits. Nevertheless, there is still very little published research directly related to this subject area. Fiorenza, L et. Al., 2018 in their research paper discussed *the use of 3D printing in dental anthropology collection* mentioned non-metric traits such as Carabelli's trait, fissure patterns, wear facets, and shoveling can be replicated and later used for teaching and research purposes.

Differences in the morphology of arches and dentition amongst various animals can play a substantial role from forensic practical, legal as well as a scientific point of view. A forensic odontologist must be aware of variations in dentition amongst different animals, which in itself is a complex and demanding part of forensic odontology. 3D printed skulls and dentitions of various animals can provide a better understanding of the phylogenic and morphologic features of the dentition. (Fig. 3)

4 **Bite mark and Pattern analysis** - With the help of 3D printing, bite marks can be compared to the suspect's dentition. As in most of the forensic fields, bite mark analysis is evaluated on a comparative basis, in which morphological features of the dentition and bite mark are matched. [41] 3D printing is a promising tool in this field because it enables the storage of the alleged suspect dentition as it was in specific time interval. If new analyses are necessary years later, the evidence from 3D printed material might be retrieved and re-analysed retrospectively. Specific

Fig. 3. Comparative dental anatomy (A) human teeth (B) non-human teeth.

intraoral scanners dedicated to the registration of surface tooth information are available in the clinical market [42]. 3D printing suspect's dentition is important once the suspect may have his/her teeth modified with restorations or any kind of morphological alteration. Parallelly, bite marks might be scanned from skin, foodstuff and objects to enable virtual 3D/3D or also printed/printed comparisons. (Fig. 4A)

Tool mark analysis and 3D printing of tool marks have been successfully achieved by Wozńiak et al. [24] and Baier et al. [43] The former reconstructed and printed blunt trauma injury whereas Baier et al. printed tool marks in case of dismemberment. For trace evidence especially in case of homicide, 3D printing can be used for matching tool marks to injuries. Impression evidence recovery is important while examining crime scene, the tire mark impression and foot wear impression scanning and printing can greatly aid in investigation [44–46]. (Fig. 4B) For better interpretation of small features, the 3D models can be scaled up and printed. These 3D printed scaled up models can also be used for court room presentation. [47]

5 **Forensic facial reconstruction–** It is a method of recreating an individual's face from their skeletal remains by utilizing tissue markers and a medium such as clay to create an approximate reconstruction. Manual facial approximation can be performed on 3D printed skulls, promoting the humanitarian forensics. Facial reconstruction also has strong impact on cultural, religious and historical aspects as it enables modelling faces of important characters. 3D printing allows the reproduction of faces reconstructed via different techniques (e.g., Russian and American approaches, for instance). In particular, some of the techniques require soft tissue modelling over a human skull – or 3D printed model of it. Printing skulls from computed tomography enables the reconstruction of faces multiple times without damaging the original skull (with potential anthropological/archaeological value).

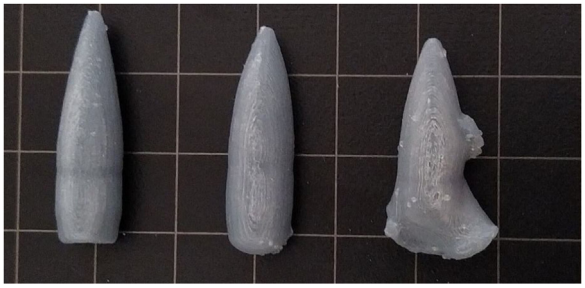

Fig. 5. 3D printed bullets (left) unfired bullets and (extreme right) fired and deformed bullets.

6 **Crime and Accident Scene Reconstruction**

3D documentation of a crime scene or accident scene has been mentioned in literature multiple times. [47,48] Scaling down these models and 3D printing them would help to demonstrate the complexities of the incident scene. Carew et al. [5] mentioned that 3D printing of multiple vehicle models in case of accident reconstruction can help to demonstrate the conjunction with the environment and also relation between collided vehicles.

7 **Ballistic Reconstruction**

3D printing can be used to print scanned bullets. It can be hypothesized that the fired bullets can be scanned and 3D printed. These can be compared with the counterparts to check for deformation. (Fig. 5) The bullet trajectories reconstructions are generated using digital imaging techniques and demonstrated using anima-

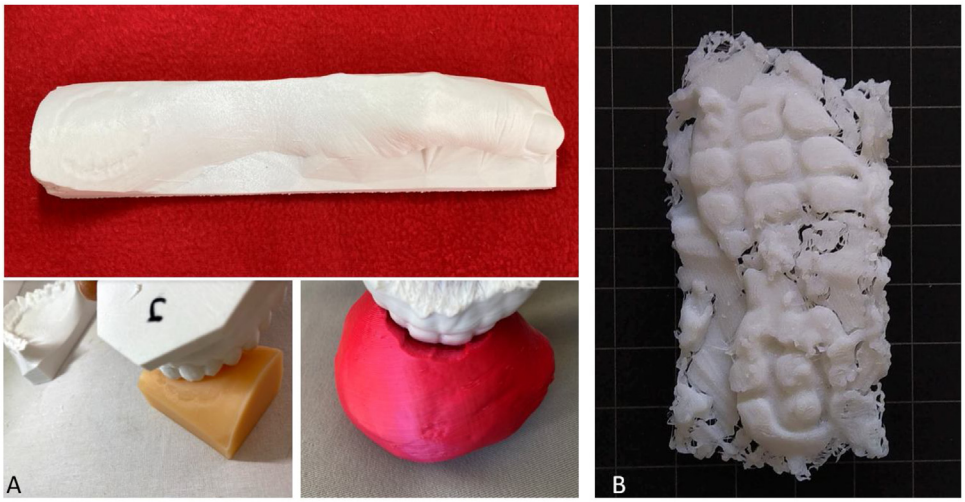

Fig. 4. (A) 3D printed bitemark on hand(top) analysis of bitemark(bottom) (B) 3D printed foot wear pattern impression.

tions, these can also be printed for presenting as evidence and demonstrating a case scenario [5,49].

8 Disaster Victim identification (DVI)

Biggs [50] reported the use of 3D printing in DVI cases, where they 3D printed maxillary and mandibular teeth from CT scan of severely charred remains which led to positive identification. The potential use of 3D printing can be for identification of charred remains in DVI situations. The utilisation of 3D scanning and subsequent printing of the charred human remains would not only facilitate in handling and analysis of burnt remains but also for court presentation.

9 Forensic Medicine

Ebert et al. [28] 3D printed models of ruptured kidney, cranium with traumatic injury and heart from volumetric scans. These 3D printed anatomical structures would not only demonstrate the relationship between the pathology and anatomical structure, but would also facilitate in examining the structure in question. These printed models can be used as demonstrative evidence in court and for teaching purpose.

10 Forensic Anthropology and Archaeology

Though the utilisation of 3D printing in anthropology and archaeology is limited, Carew et al. [25] conducted a study for assessing accuracy of 3D printing in anthropology. They successfully 3D printed skeletal remains using different 3D printers and demonstrated the accuracy, dimensional stability and repeatability in metrics. In forensic archaeology digitization of mass graves and archaeological sites is common [51,52] however to best of our knowledge, there is no empirical research on 3D printing in archaeological sites.

5. Advantages and Drawbacks of 3D printing in Forensics

5.1. Advantages

The principal advantage of 3D printing in forensic evidence reconstruction is that the replica can be handled without restrictions and examined spontaneously from all the aspects. 3D printed models can be used for visual presentation of anatomy in court. It has been noted by many authors that the evidentiary findings should be represented and explained in clear way along with maintaining the integrity of evidence. [27] Presentation of human remains may be disturbing and in few countries the presentation of human remains is not allowed [5]. Photographs have been used for presentation in court, however it has been noted that there is loss of information in z-axis [27]. Errickson et al. [27] conducted a study to investigate the visualisation techniques suitable for better understanding in court, they concluded that juror understanding increased with the use of 3D modalities. It has been noted by authors [29–32] that 3D scanning and printing are non-invasive techniques not only for demonstration in court but also for reconstruction of fragmented and missing skeletal remains especially in case of fragile remains. It has been also been mentioned by many authors that these 3D printed evidence can be revisited and re-evaluated in case of decomposition, burial or destruction in case of original evidence. Owing to the non-destructive and non-invasive nature of the technology the 3D printing in forensics is a humanitarian approach as the evidence is analysed, investigated and visualised merely by touching it and thereby maintaining the integrity of the evidence.

5.2. Drawbacks

The major drawback of utilising 3D printing in forensics is that there is very little empirical data on the accuracy of 3D prints from forensic perspective and thus leading to issues of admissibility in courts. There are no specific ethical or legal guidelines developed for 3D printing of forensic evidence. The typical characteristics of the evidence like bone density, the surface of evidence (example: roughness, shine or coarseness) cannot be replicated at present. It has also been mentioned that the modelling parameters do affect the printing quality, there is no specific guidelines for processing of the scans which raises the questions regarding the resemblance of the reconstructed object to evidence. [25,53] Presently FDM and SLA technology are widely used for 3D printing, that prints the object using rafts, brims and support structures. There is need to remove these support structures and perform post-processing to obtain a finished replica [54], these may in turn affect the accuracy of the model. One of the limitations listed by experts is that the 3D models created can be shared, downloaded, modified and printed which may affect the integrity of evidence [54]. The special setup and trained experts are also required for practical execution.

6. 3D printing in forensics- Indian scenario

3D printing in forensics is still an emerging technology in India. There are few instances where 3D scanning has been used documentation in India. [55] The researches are at proof-of-concept stage, where the limitation and advantages of the technology are still been tested [56]. Johnson et al. [29] conducted a study using 3D scanning and printing, where the missing teeth were reconstructed from the intra-alveolar morphology. This study was an initial attempt, where 3D scanning and printing was utilised for reconstruction of post-mortem missing teeth. In a series of studies [30–32] the authors utilised 3D scanning and printing for reconstruction of fragmented dental and osseous remains. They successfully reconstructed dental remains with overall morphological error of 0.0526 ± 0.05 mm [32] and osseous remains within the error range of +/-2.00 mm [30,31]. In the same study [31] the authors were able to reconstruct bilaterally missing zygomatic process using 3D technology. Chaudhary et al. [57] in their review have also highlighted the importance of 3D printing in forensics.

Key points/suggestions regarding development of 3D printing in forensics in India:

- More researches are indicated for validation of metrics and surface evaluation of 3D prints obtained using different 3D printing technology from forensic context.
- Identifying different forensic disciplines where 3D technology can be used effectively and establishing multi-disciplinary approach to develop best practices in forensics using 3D technology.
- Formation of standard operating protocols for obtaining 3D scans and setting parameters for 3D modelling for printing.
- Developing protocols for setting parameters for printing (layer height, temperature, printing speed) and post-processing procedures for creating accurate replicas of evidence.
- Formation of legal and ethical guidelines for utilisation of 3D technology and presentation of reconstructed evidence.

7. Conclusion

3D printing technology has proved to be a boon in medical and dental fields, it has specifically made the surgeries easier. However, the utilisation of this technology in forensics is still in infant

stage in India. The non-invasive nature of the technology can prove to be of great advantage in forensics. The major advantage of the 3D printed model is it allows better visualisation, interpretation and understanding. 3D printing is also an humanitarian approach as the evidence is reconstructed without touching the evidence, thereby not damaging the actual evidence. The scans of the original evidence can be scaled and printed for analysis and used as demonstrative evidence in court. The results obtained in preliminary studies have proved that the technology provides accurate results. With further exhaustive researches, utilisation of newer methods of 3D printing and sensitization among the forensic practitioners in India, the technology can transform the field of forensics in India.

Declaration of competing interest

Authors declare no conflict of interests.

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